DRAINAGE DENSITY AND RELATIVE RELIEF IN HUMID STEEP MOUNTAINS WITH FREQUENT SLOPE FAILURE

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ABSTRACT

Previous studies in Japanese mountains have shown that drainage density (*D*) correlates negatively with relative relief (*R*) and the erosion rate (*E*), whereas elsewhere both *R* and *E* correlate positively with *D*. To investigate the inconsistency, this paper compares two types of *D–R* relations for eight mountain river basins in central Japan. *R* is computed from a digital elevation model for 1109 morphometric samples of area 0·5 km × 0·5 km. Drainage networks in these cells were first constructed by map criteria applied previously in Japan – deeply notched V-shaped contours with an angle <53°. The resulting *D* correlates negatively with *R*, confirming preceding studies. When drainage lines along shallower hollows were added, however, the calculated *D* is essentially constant. These relations arise from active landsliding in high-relief terrains, which has eroded steep channel banks into gentle ones. The decline of channel banks with increasing *R* is accelerated in terrains underlain by soft rocks, because of rapid erosion. The constant *D* for all the drainage lines indicates a uniform frequency or spacing of ridges and hollows on hillslopes in rugged humid mountains. Because the *D–R* and *D–E* relations for Japan reflect a uniquely Japanese physiographic setting characterized by frequent landsliding, they differ from those relations for other regions where channelization by gullying predominates. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Drainage density (*D*), which has been defined as total stream length per unit area of a river basin (Horton, 1932, 1945), has often been used to express the degree of fluvial dissection. Numerous researchers have measured values of *D* from topographic maps and have analysed variables controlling *D*. The results indicate that *D* is related to climate (Chorley, 1957; Chorley and Morgan, 1962; Gregory and Gardiner, 1975), vegetation (Melton, 1958), bedrock geology (Tanaka, 1957; Smith, 1958; Wilson, 1971), time (Ruhe, 1952; Tokunaga *et al*., 1980; Kashiwaya, 1983), and the hypsometric integral (Strahler, 1952). Some researchers (e.g. Yatsu, 1950; Schumm, 1956) have also indicated that *D* is strongly influenced by relative relief (*R*), the maximum height dispersion of a terrain normalized by its length or area. The climatic and geologic controls of *D* are widely recognized and well understood: *D* tends to be large in arid regions of sparse vegetation, in temperate to tropical regions subjected to frequent heavy rains, and in areas underlain by rocks with low infiltration capacity or transmissibility (Tanaka, 1957; Carlston, 1963; Cotton, 1964; Madduma Bandara, 1974; Gregory and Gardiner, 1975; Suzuki *et al*., 1985). By contrast, the general relation between *R* and *D* remains uncertain. In humid badlands, Schumm (1956) found a positive correlation between *D* and the relief ratio, basin height divided by basin length. According to Gardiner *et al*. (1977), such a correlation is plausible from the widely observed inverse correlation between both *D* and *R* and basin area. An experimental analysis of rill erosion performed by Mosley (1972) also revealed that *D* was positively correlated with ground slope. In contrast, Mino (1942) and Yatsu (1950) pointed to a negative correlation between *D* and *R* for mountainous regions in Japan. According to

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Yatsu (1950), the following relation between D (km/km^2) and the maximum relief within a unit area of 11 km^2 (R_{11} in m) holds for the Chichibu mountain range in central Japan,

$$R_{11} = ae^{-bD} \quad (1)$$

where $a = 2{\cdot}09 \times 10^3$ and $b = 0{\cdot}578$. These findings indicate that the characteristics of the D–R relation may vary according to regional factors. A mathematical modelling of hillslope development by Kirkby (1987) also suggests that the relation between D and ground slope differs depending on dominant hillslope processes. However, because such a difference has received limited attention so far, variables controlling the D–R relation remain to be determined.

The D–R relation is also pertinent to that between sediment yield and drainage development. Studies of dam sedimentation rates in Japan have indicated that hillslope erosion rates increase with R (Ohmori, 1978; Mizutani, 1981), which is also plausible from analysis of the size of Japanese alluvial fans (Oguchi and Ohmori, 1994). Thus, the negative correlation of D with R reported by Mino (1942) and Yatsu (1950) suggests that rapid erosion occurs in the terrain characterized by low drainage density. However, Japanese mountains may be eroded mainly by heavy rains that can generate large flows on hillslopes (Tsukamoto, 1973), which casts doubt on the negative correlation between D and erosion rates. In addition, previous studies in the United States pointed to a positive correlation between D and sediment yield (Schumm, 1956; Hadley and Schumm, 1961). Thus, it is necessary to re-examine whether the negative correlation between D and R is a general characteristic of Japanese mountains. Furthermore, if the negative correlation holds, it should be examined for consistency with processes of hillslope erosion and sediment yield.

To address the unsolved questions above, this paper first examines the D–R relations for mountain river basins in central Japan and then interprets the observed relations in terms of current hillslope processes, with special reference to the effect of slope failure on landform development.

THE STUDY AREA

Eight mountainous drainage basins surrounding the Matsumoto basin of central Japan were selected for study (Figure 1). The basins are located in the Northern Japanese Alps and adjacent mountains, which have the highest relief among non-volcanic ranges in Japan (Ohmori, 1978). The basins, which all have alluvial fans in

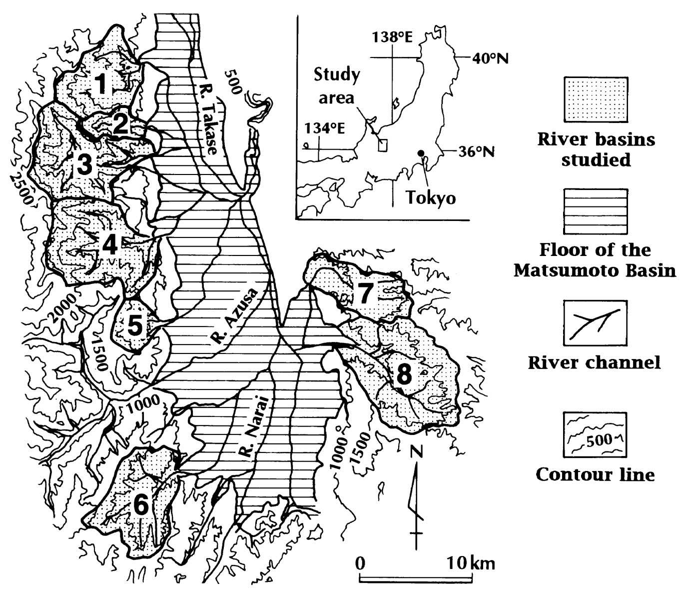

Figure 1. Location map of study area, showing eight river basins: (1) Chi, (2) Ashima, (3) Nakafusa, (4) Karasu, (5) Kurosawa, (6) Kusari, (7) Metoba, (8) Susuki. Contour interval 500 m

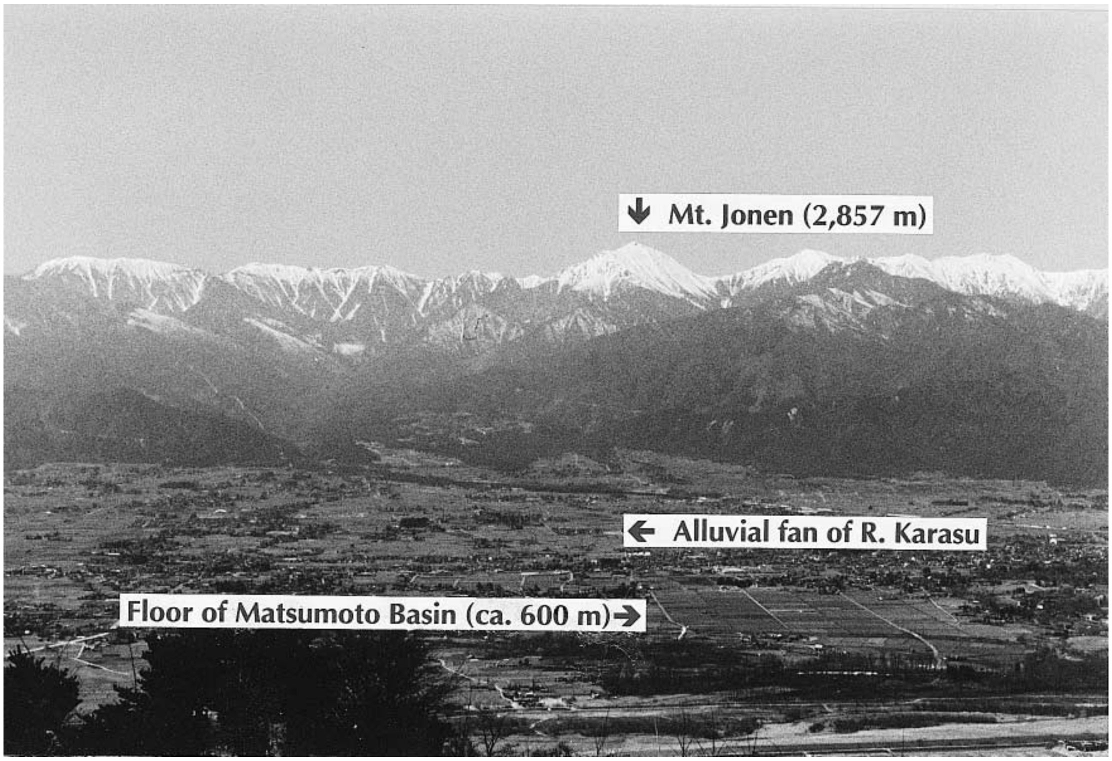

Figure 2. Karasu river basin from the east. The source basin of the alluvial fan was investigated in this study

their lowest reaches, consist mostly of steep valley-side slopes, with minor fluvial terracing along trunk streams and major tributaries (Figure 2). The general features of these basins suggest the ‘ridge and ravine topography of humid mountains’ defined by Hack (1960). Area of the basins ranges from 12 to 78 km^2, maximum altitude from 1935 to 2922 m, altitude at the fan apex from 720 to 830 m, and relief ratio from 0·10 to 0·29. The basins are underlain by five major rock types: Palaeozoic–Mesozoic sediments, Mesozoic granites, Neogene sedimentary and plutonic rocks, Quaternary volcanics, and Quaternary terrace gravels (Figure 3).

Digital maps and geological data for the study area had already been compiled (Oguchi, 1988a). The digital maps include elevation data of lattice points plotted at 125 m intervals. Classification and mapping of hillslope units (Oguchi, 1988b, 1992) based on aerial photo interpretation and tephrochronological field surveys of the basins revealed that most of the hillslopes experienced slope failure and gullying during the Late Glacial (10 to 13 ka BP) and Holocene.

Most hillslopes are thickly forested except for recent landslide scars, the ridges of high mountains exposed to strong winds, and areas subjected to recent logging. The annual precipitation observed at a station near the study area (Taisho-ike Pond Station, 1495 m in altitude) is about 2500 mm (Japan Meteorological Agency, 1959). Heavy rains generally fall in June, July and September from storms associated with the Polar Front and typhoons. As occurs often elsewhere in Japan, slopes in the study area fail frequently in storms despite protection by the thick forest cover, which accounts for numerous landslide scars. In Japan, the average frequency of a landslide event in an area of the size of the studied basins (*c*. 10 to 80 km^2) is of the order of one in 10 years, which corresponds to the recurrence interval of storm rainfall exceeding 50 mm h^{-1} (Oguchi, 1994a).

Mountains in the study area may have undergone rapid tectonic uplift and concurrent erosion during the Quaternary (Research Group for Quaternary Tectonic Map, 1969; Ohmori, 1978). On the other hand, Ikeda (1990a,b) offered an alternative hypothesis that the Quaternary uplift of these mountains has resulted not from tectonic stress but from isostatic rebound in response to valley deepening by erosion. Despite different opinions on the cause of uplift, it is agreed that the mountains have increased in relative relief together with valley erosion during the Quarternary. Thus, in the study area, terrains with large R values are thought to have been eroded more extensively than those with small R values.

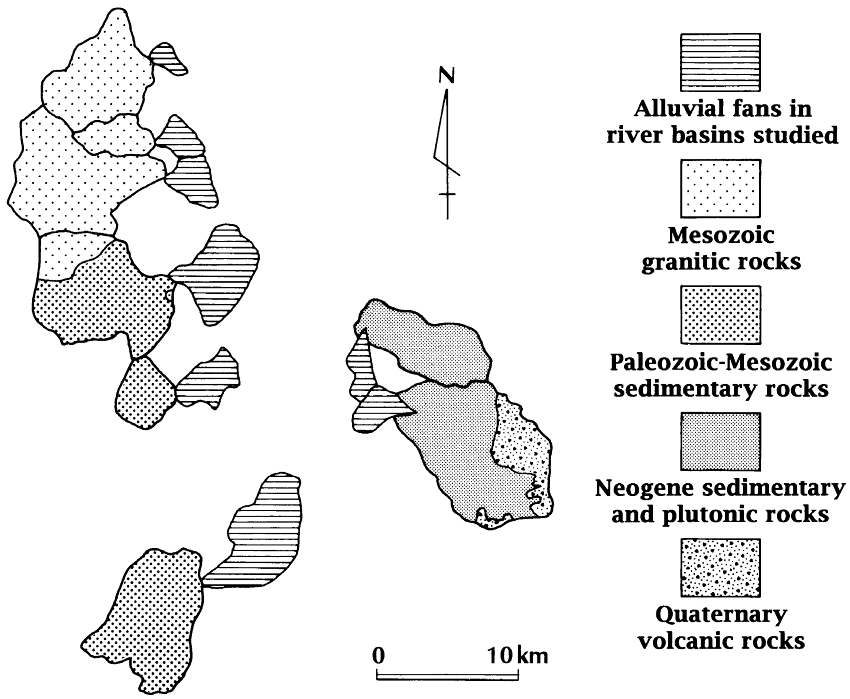

Figure 3. Geological map of the eight river basins studied, simplified after Nagano Prefecture (1986). Quaternary terrace gravels above the fan apex are not shown because of their limited extent along streams

DATA COLLECTION

Drainage networks of the eight basins were constructed from 1:25000 topographic maps of the Geographical Survey Institute of Japan. The contour interval is 10 m. Two methods have been proposed to determine stream lengths on topographic maps: measuring streams shown in blue, and measuring drainage lines suggested by V-shaped contours. Because the ‘blue line’ method is inadequate to describe actual stream networks (Morisawa, 1957; Gregory and Walling, 1973), I used the second method, ‘contour crenulation’. Some previous researchers determined a maximum notching angle of the V-shaped contour for applying the contour crenulation method (Mino, 1942; Yatsu, 1950; Bauer, 1980), whereas some used all the V-shaped contours (Carlston, 1963; Takayama, 1972; Mark, 1983). In Japan, Mino (1942) and Yatsu (1950) adopted 53° for the maximum angle; that is, drainage lines are drawn when the horizontal depth of the notched contour exceeds its width. To compare results of this study with previous ones, drainage networks were first constructed using the <53° criterion proposed by Mino (1942) and Yatsu (1950), and then drawn using all the notched contours including those with angles exceeding 53° (Figures 4 and 5). The drainage included in the former networks (<53°) were designated ‘d-type (deep type) drainage’, those in the latter (>53°) as ‘s-type (shallow type) drainage’. These drainage nets constructed from topographic maps are not identical with those mapped in the field. However, Mark (1983) has shown that the stream lengths inferred from the contour crenulations of 1:24000 topographic maps in the United States are strongly related to those surveyed in the field. Thus, the drainage nets derived here are suitable to examine the similarities and differences in stream distribution within the study area.

Next, the basins above the fan apex were subdivided into 500 m × 500 m square cells, each of which included 25 lattice points of the digital elevation maps (Figure 6). The 1659 cells included 550 located on basin divides. The value of *D* for each cell was calculated from the original definition of Horton (1932, 1945), although more

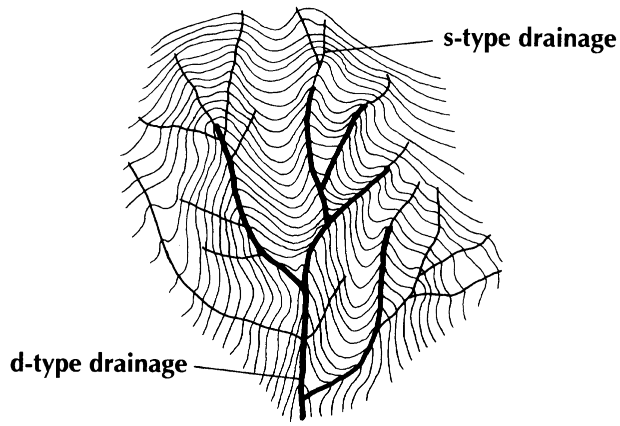

Figure 4. Definition of d-type and s-type drainages. The d-type drainage was constructed using deeply notched V-shaped contours with an angle of less than 53° (i.e. horizontal depth of the notched contour exceeds its width). The s-type drainage was constructed using the shallowly notched contours with an angle of more than 53° (i.e. depth < width)

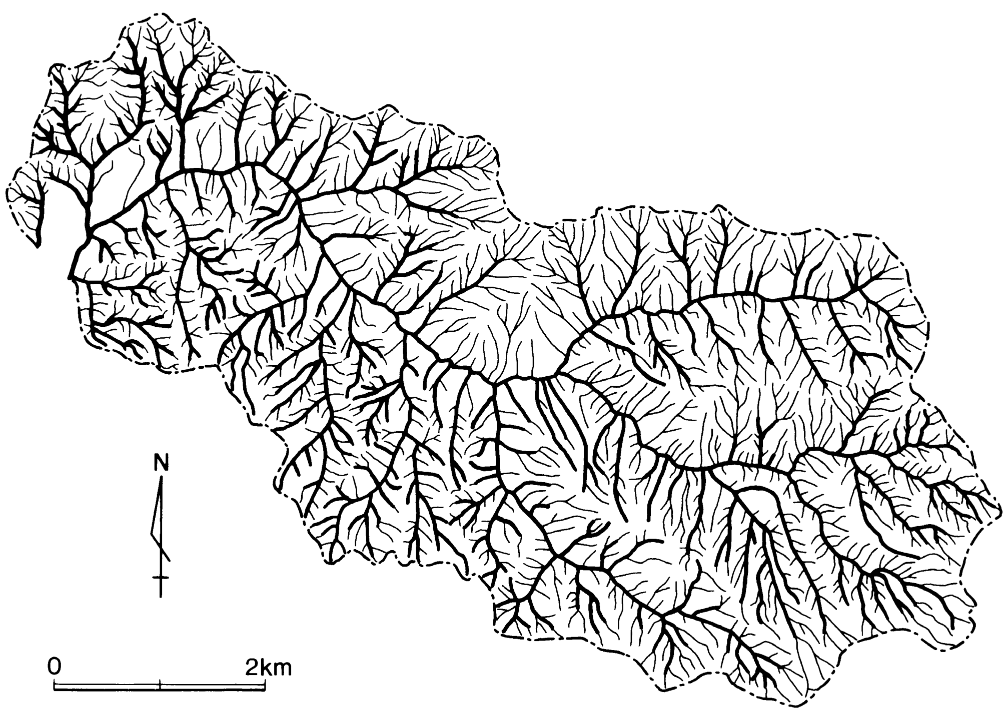

Figure 5. Drainage nets in Metoba river basin. Thick lines show d-type drainage, and thin lines show s-type drainage

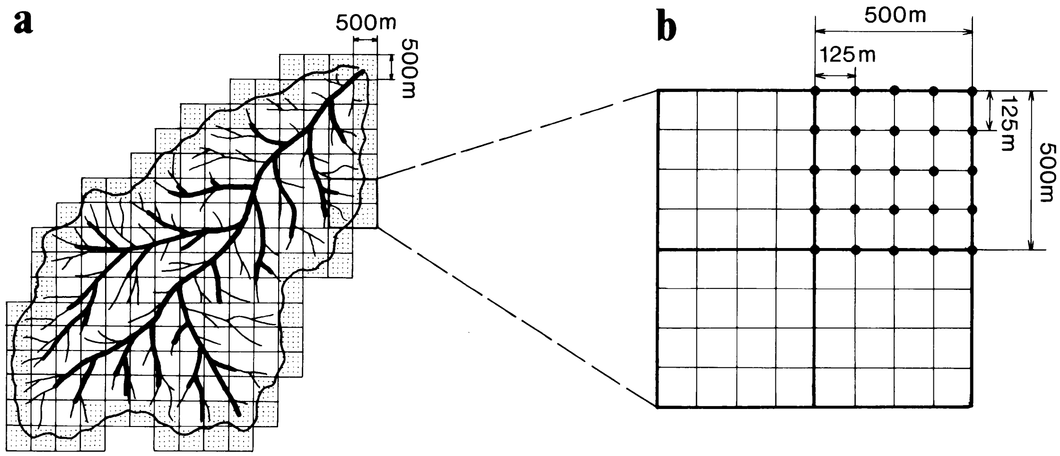

Figure 6. Grid system used for morphometry. (a) Sampling a river basin with a 500 m × 500 m grid. Dotted cells on the basin divide are not used for analyses. (b) Lattice points of digital elevation map with a 125 m × 125 m X, Y interval

rapid methods to approximate D have been devised (Carlston and Langbein, 1960; McCoy, 1971; Gregory and Gardiner, 1975). First, the total lengths of d-type and s-type drainages were measured for each cell and divided by its area. Three values of D (in km/km^2) can be calculated: D for the d-type drainage (D_d), that for the s-type drainage (D_s), and that for the two combined ($D_t = D_d + D_s$).

In this paper, R is defined as the difference between the maximum and minimum altitudes within a cell of 500 m × 500 m. R values (in m) were calculated from the digital maps, although those for the 550 cells located on divides were indeterminate – their areas within the divide are smaller than 500 m × 500 m. Consequently, the data were completed for the 1109 cells that are removed from divides. Because the size of the selected cells is constant, R is equivalent to average slope inclination in a cell.

The geology of each cell was defined as the general type of bedrock occupying the largest area. Bedrock types were determined from geological maps compiled by Nagano Prefecture (1986). Among the 1109 cells, 357 are in Mesozoic granitic rocks, 355 are in Palaeozoic–Mesozoic sedimentary rocks, 281 are in Neogene sedimentary and plutonic rocks, 61 are in Quaternary volcanic rocks, and 55 are in Quaternary terrace gravels.

DRAINAGE DENSITY–RELATIVE RELIEF RELATIONS

To obtain generalized D–R relation, values of D_d, D_s and D_t for the 1109 cells were first categorized by geology and R in 50 m intervals or bins. Because all eight basins are located within a relatively small region, the differences in climate are negligible. Next, the mean and standard deviation of D were calculated for each 50 m R bin that includes at least five cells (Table I). Figure 7A, a plot of mean D_d values against model values of R for each bin, shows that D_d decreases with increasing R for each type of geology. For each value of R, D_d for Mesozoic granitic rocks is systematically larger than that for the other rock types.

Figure 7B similarly illustrates the relation between D_s and R for different geology. In contrast to the D_d–R relation, D_s increases with R. Such a tendency is also evident from field observation of hillslope forms. Figure 8 shows two typical hillslopes in the study area, characterized by different R values. The high-relief terrain (A) has many shallow landslide scars and few deep and narrow channels, while the opposite is true for the low-relief terrain (B).

Table I. Mean and standard deviation (in parentheses) of drainage density by relative relief and bedrock geology.

Relative relief (m)	Palaeozoic–Mesozoic sedimentary rocks				Cretaceous granitic rocks				Neogene sedimentary and plutonic rocks				Quaternary volcanic rocks				Quaternary terrace gravels			
	N	D_d (km/km^2)	D_s (km/km^2)	D_t (km/km^2)	N	D_d (km/km^2)	D_s (km/km^2)	D_t (km/km^2)	N	D_d (km/km^2)	D_s (km/km^2)	D_t (km/km^2)	N	D_d (km/km^2)	D_s (km/km^2)	D_t (km/km^2)	N	D_d (km/km^2)	D_s (km/km^2)	D_t (km/km^2)
1–50	0	–	–	–	0	–	–	–	0	–	–	–	0	–	–	–	2*	–	–	–
51–100	0	–	–	–	0	–	–	–	5	6·02 (1·77)	4·90 (1·00)	10·9 (1·18)	0	–	–	–	8	4·81 (1·57)	2·96 (0·96)	7·78 (1·81)
101–150	4*	–	–	–	5	5·62 (1·67)	5·98 (2·03)	11·6 (2·07)	18	5·23 (1·49)	6·50 (1·77)	11·7 (1·74)	2*	–	–	–	19	5·34 (1·71)	4·84 (2·53)	10·2 (2·25)
151–200	20	4·83 (2·17)	5·50 (1·72)	10·3 (2·86)	16	6·59 (1·72)	6·70 (2·20)	13·3 (2·54)	52	4·67 (1·67)	6·07 (1·80)	10·7 (1·70)	16	5·88 (2·05)	5·91 (1·42)	11·8 (1·48)	19	4·78 (2·47)	5·24 (2·74)	10·0 (3·34)
201–250	68	3·86 (2·12)	5·82 (2·34)	9·68 (2·52)	39	5·26 (2·18)	6·28 (2·32)	11·5 (2·12)	81	3·61 (1·60)	6·48 (1·63)	10·1 (1·74)	19	3·76 (2·15)	6·87 (1·54)	10·6 (2·27)	6	2·85 (1·02)	5·82 (2·47)	8·67 (2·52)
251–300	99	3·31 (1·93)	6·48 (2·77)	9·79 (2·64)	48	4·64 (2·04)	7·01 (2·52)	11·7 (2·47)	70	3·56 (1·58)	6·47 (1·38)	10·0 (1·51)	18	2·57 (1·75)	7·28 (1·79)	9·86 (2·01)	1*	–	–	–
301–350	86	3·07 (2·04)	7·10 (2·43)	10·2 (2·76)	70	4·56 (2·04)	7·52 (2·21)	12·1 (2·45)	34	2·74 (1·68)	7·23 (1·42)	10·0 (1·69)	3*	–	–	–	0	–	–	–
351–400	51	2·76 (1·66)	7·55 (2·29)	10·3 (2·48)	81	3·88 (2·06)	7·99 (2·28)	11·9 (2·56)	18	2·15 (1·18)	8·28 (1·77)	10·4 (1·46)	1*	–	–	–	0	–	–	–
401–450	21	3·25 (2·20)	8·13 (2·25)	11·4 (2·96)	60	4·16 (1·85)	8·27 (1·85)	12·4 (2·48)	3*	–	–	–	1*	–	–	–	0	–	–	–
451–500	5	3·02 (1·55)	8·24 (2·23)	11·3 (3·64)	28	4·28 (1·88)	8·24 (1·93)	12·5 (2·47)	0	–	–	–	0	–	–	–	0	–	–	–
501–550	1*	–	–	–	9	4·12 (1·23)	7·87 (1·69)	12·0 (1·89)	0	–	–	–	0	–	–	–	0	–	–	–
551–600	0	–	–	–	0	–	–	–	0	–	–	–	0	–	–	–	0	–	–	–
601–650	0	–	–	–	1*	–	–	–	0	–	–	–	0	–	–	–	0	–	–	–

N, number of 500 m×500 m sample cells (asterisk indicates less than five); D_d, density of d-type (deep) drainage; D_s, density of s-type (shallow) drainage; D_t, density of all drainages. See Figure 4 for definitions. Mean densities for categories with fewer than five cells were not calculated

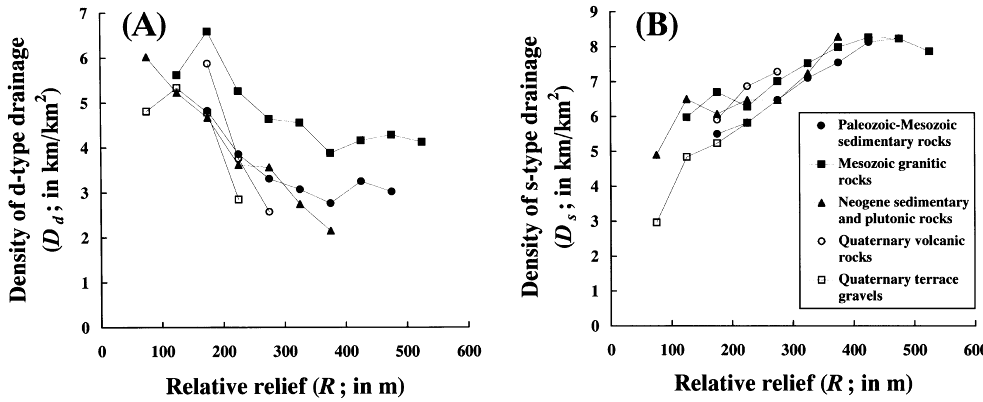

Figure 7. Relations between drainage density (D) and relative relief (R) for d-type drainage (A) and s-type drainage (B), for five types of geology. D_d decreases with increasing R, but D_s increases with increasing R. D_d for Mesozoic granitic rocks is systematically larger than that for the other rock types

(A)

(B)

Figure 8. (A) Hillslopes in the Kurosawa river basin (high relative relief), developed on Palaeozoic–Mesozoic sedimentary rocks. Hollows including landslide scars (s-type drainage) are abundant, but deep and narrow channels (d-type drainage) are much less so. (B) Hillslopes in the Metoba river basin (low relative relief), covered with Neogene sedimentary and plutonic rocks. Deep and narrow channels (d-type drainage) are abundant but hollows (s-type drainage) are much less so

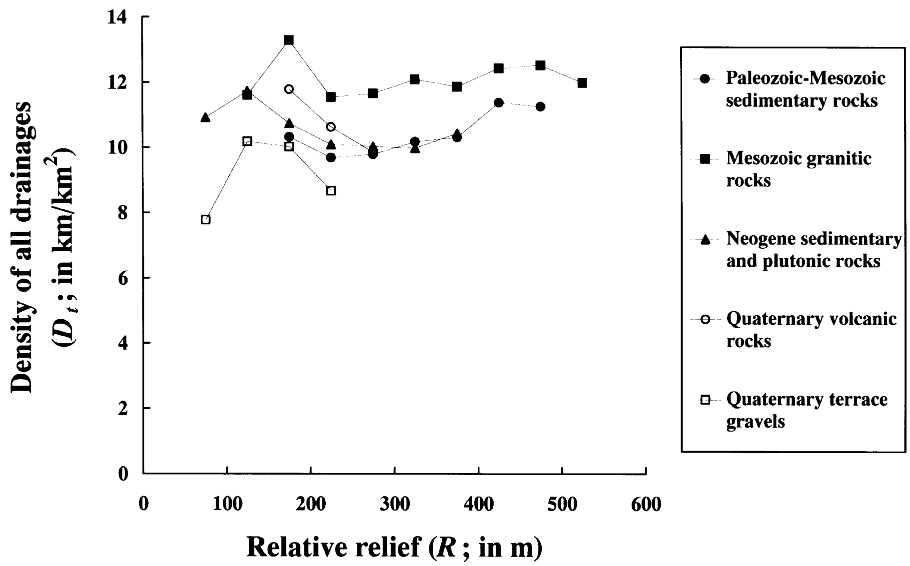

Figure 9. Relation between the density of all drainages combined (D_t) and relative relief (R) for each type of geology. D_t tends not to change with R. Although D_t for Mesozoic granitic rocks is systematically higher than that for the other rock types, D_t generally falls in a range between 8 and 13 km/km^2, irrespective of rock types and the values of R

Figure 9 illustrates the relation between R and the combined D_t for the five rock types. D_t tends to hold constant for each class of geology despite the change in R. Thus the rate of decrease in D_d with increasing R is almost equivalent to the rate of increase in D_s with R. To enhance the changes in D_d and D_s with R, the ratio of D_s to D_d was plotted against R (Figure 10). As expected from Figure 7, D_s/D_d increases with R. The rate of increase in the ratio differs as a function of geology. Table II shows increment in the ratio with each 50 m increase in R. Averages of this value diminish in the following order: Quaternary volcanic rocks, Neogene sedimentary and plutonic rocks, Quaternary terrace gravels, Palaeozoic–Mesozoic sedimentary rocks, and Mesozoic granitic rocks. Figure 10 also shows that the D_s/D_d difference according to geology is small in low-relief terrains but becomes conspicuous in high-relief terrains.

Figure 9 shows that D_t for Mesozoic granitic rocks is systematically higher than that for the other types of geology, and D_t tends to be the lowest for Quaternary terrace gravels. Despite the differences according to geology, mean values of D_t generally fall into a range between 8 and 13 km/km^2. This value is comparable to or smaller than D for arid regions worldwide, but larger than the previously reported D for humid temperate regions and intertropical regions (Gregory and Gardiner, 1975, Figure 2). In summary, D–R relations in the study area vary with the types of the drainage included in the stream nets as well as bedrock geology.

DISCUSSION

Change in drainage density with relative relief

Because the d-type drainages were identified using the criteria of Mino (1942) and Yatsu (1950), the D_d–R relations in Figure 7A agree with the negative correlation between D and R reported by these authors. Thus, the decrease in D_d with an increasing R is considered to be a general characteristic of Japanese mountains. The graphs of the D_d–R relations in Figure 7A are concave overall, which also agrees with Yatsu's (1950) result shown by Equation 1.

These relations, however, no longer hold if s-type drainages are included in the stream nets. D_t tends not to change with increasing R (Figure 9), because the increase in D_s compensates the reduction in D_d. I interpret this

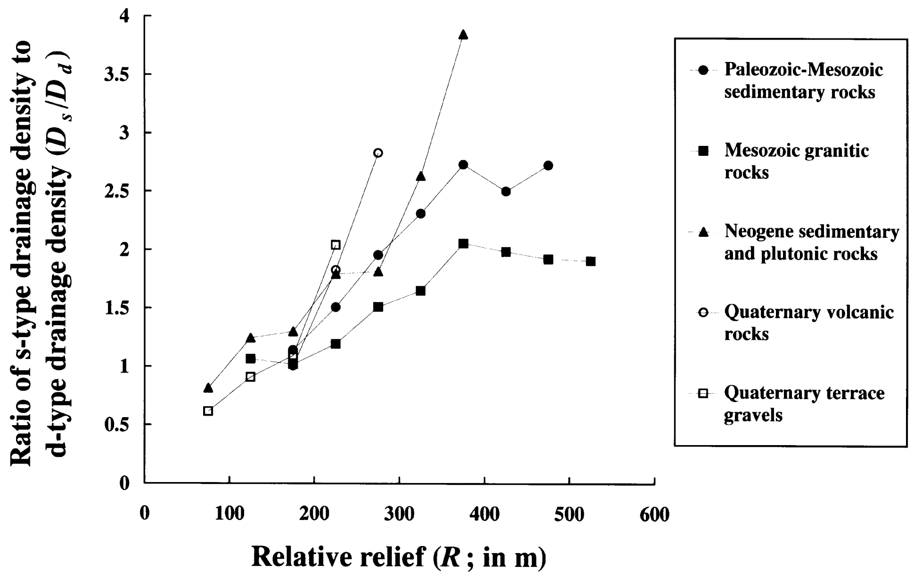

Figure 10. The ratio of the density of s-type drainage (D_s) to that of d-type drainage (D_d) verses relative relief (R). The ratio tends to increase with increasing R. The rate of increase is highest for Quaternary and Neogene rocks, intermediate for Palaeozoic–Mesozoic sedimentary rocks, and smallest for Mesozoic granitic rocks

Table II. Increment in ratio of s-type drainage density (D_s/D_d) with each 50 m increase in relative relief

Range of mode of relative relief (m)	Palaeozoic–Mesozoic sedimentary rocks	Mesozoic granitic rocks	Neogene sedimentary and plutonic rocks	Quaternary volcanic rocks	Quaternary terrace gravels
75–125	—	—	0·429	—	0·292
125–175	—	–0·047	0·057	—	0·187
175–225	0·369	0·177	0·491	0·822	0·946
225–275	0·448	0·317	0·024	1·004	—
275–325	0·356	0·139	0·820	—	—
325–375	0·420	0·407	1·217	—	—
375–425	–0·230	–0·072	—	—	—
425–475	0·226	–0·063	—	—	—
475–525	—	–0·015	—	—	—
Average	0·265	0·105	0·506	0·913	0·475

compensation to indicate that, with the increase in R through valley deepening, d-type (deep) drainages are gradually replaced by s-type (shallow) drainages. Two possible explanations can be given for this proposed change in drainage type in high-relief terrains: (1) valleys and hillslope hollows are infilled due to increased sediment supply from adjacent slopes; and (2) the angle of channel banks rapidly diminishes owing to activated erosion. Field surveys in the study area (Oguchi, 1988b) have revealed that the sediment thickness in hillslope hollows is generally less than 1 m, because of effective flushing during heavy storms. Thick sedimentary fill, if any, is confined to near the junctions of the channels and higher-order streams, where small alluvial cones and talus slopes occasionally form. Thus, in upper to middle hillslopes, there are no thick channel-fill sediments or 'colluvium wedges' of the sort that have been reported from the Pacific Coastal Ranges of the United States (Montgomery and Dietrich, 1989; Reneau *et al*., 1990). Nevertheless, because s-type drainages mainly occur at the upper to middle hillslopes (Figure 5), the burial of d-type drainages cannot account for the decrease in D_d with the increase in R.

Much to the contrary, erosion of the channel banks along d-type drainages does occur in the study area. As indicated by Moriya (1972), steep valley sides in Japanese mountains consist mainly of shallow plain- to hollow-shaped landslide scars and deep channels. The scars and channels can be correlated with the 'incised slopes' or 'dissected slopes' in the landform classification maps of Oguchi (1988b, 1992, 1994b,c). Field surveys and aerial photographic interpretation revealed that the majority of steep hillslopes in the study area are occupied by the incised slopes (Oguchi, 1988b, 1992). Because slope stability is low, many recent failures occur near the convex break in slope that separates channel banks from the shallow hollow on a hillslope, indicating that the channel banks along d-type drainages are declining by slope failure. Such a process may predominate more on steeper slopes, because, in Japanese mountains, the magnitude of slope failure in terms of sediment volume produced consistently increases with R (Oguchi, 1994a). Consequently, the decrease in D_d with increasing R can be attributed to active landsliding on steep hillslopes, which also explains the negative correlation between D_d and sediment yield.

The above interpretation is consistent with Tsukamoto's hydrogeomorphological model for the development of a 'zero-order' basin. The zero-order basin has been defined as a set of convergent hollow-shaped slopes located above the head of a perennial first-order stream (Tsukamoto, 1973). This definition suggests that the s-type drainages are comparable to flow lines within zero-order basins. According to Tsukamoto (1973) and Tsukamoto *et al*. (1982), hillslope failure in Japanese mountains mainly occurs within zero-order basins, associated with a temporary rise in the water table during heavy rains. This observation reaffirms that slope failure plays a crucial role in the development of s-type drainages.

Although neither D_d nor D_t for Japanese mountains increases with an increasing R, surveys in badlands topography of the United states revealed a positive correlation between D and R (Schumm, 1956; Smith, 1958). In the Pacific Coastal Range of the United States, Montgomery and Dietrich (1992) found that the drainage area above channel heads decreases with increasing local slope, which also points to the positive correlation of D with R. In these areas channels develop mainly by gullying of unconsolidated sediments, including colluvium wedges. Such processes result when overland flow exceeds the threshold of surface erosion (Kirkby and Chorley, 1967) or from small-scale landslides at channel heads (Reneau *et al*., 1990). Geomorphic analyses of the erosional threshold performed by Dietrich *et al*. (1992) have revealed that the source area necessary to maintain the unit width of channel heads tends to decrease with an increasing ground slope. This observation indicates that the positive correlation between D and R reflects the geomorphic threshold for gullying. In conclusion, the regional difference in the D–R relations can be attributed to differences in the dominant hillslope process: widespread slope failure on valley-slide slopes in steep Japanese mountains, gullying in unconsolidated sediments for some regions in the United States.

Effects of geology on drainage density – relative relief relations

The rate of increase in the D_s/D_d ratio with R, which indicates the degree of change in drainage types due to channel bank decline, differs markedly according to geology (Figure 10, Table II). This difference is a function of rock strength. Field observations in the area have shown that Palaeozoic, Mesozoic and Tertiary rocks are consolidated, whereas Quaternary volcanic rocks include intercalated layers of weak clastic sediments, and Quaternary terrace gravels remain unconsolidated. Miki and Furutani (1983) have compiled the known data of longitudinal wave velocity, measured in the field for the pre-Quaternary rocks in the study area. This property has often been used by civil engineers as an indicator of the mechanical strength of bedrock, because it is positively correlated with the compressive strength and the Young's modulus of rocks (Okubo and Terasaki, 1971). The compiled velocity values for Mesozoic granitic rocks range from 4·00 to 5·40 km s^{-1} (4·56 km s^{-1} average), those for Palaeozoic–Mesozoic sedimentary rocks from 3·93 to 5·24 km s^{-1} (4·38 km s^{-1}), and those for Neogene sedimentary and plutonic rocks from 1·70 to 3·82 km s^{-1} (2·75 km s^{-1}). These values and the field observation of rock facies indicate that the strength of bedrock increases in the following order: Tertiary and Quaternary rocks, Palaeozoic–Mesozoic sedimentary rocks, and Mesozoic granitic rocks. This order corresponds to the rate of change in D_s/D_d with increasing R: as the rock strength increases, the rate decreases. I interpret this correlation to indicate that channel banks along the d-type drainage lines have declined more in weaker rocks.

The above interpretation can be tested and validated by known relations between rock properties and valley forms. Suzuki *et al*. (1985) have shown that the valley sides in hilly lands of Japan steepen with the increase in rock strength. In North Japan, Tanaka (1990a,b) also found that the angle of valley walls on weak rocks rapidly declines by frequent landsliding, whereas slopes on stronger rocks remain unchanged or even increase with time. Thus, I conclude that differences in mechanical strength of the bedrock account for the different relations of R to the D_s/D_d ratio, because rock strength has markedly controlled the erosional development of valley sides through slope failure.

The influence of geology on drainage density is also evident in the D_d–R relations and D_t–R relations (Figures 7A and 9), in which D reaches its highest values in Mesozoic granitic rocks. This observation most likely reflects the difference in infiltration capacity. In western Japan, Tanaka (1957) also found that D was systematically higher in granitic rocks than in Palaeozoic–Mesozoic sediments. From field experiments, he attributed this difference to lower infiltration capacity of granitic rocks. In Figure 9, the influence of infiltration capacity is also detectable from the low value of D_t for Quaternary terrace gravels, which are the most permeable of the five rock types.

Uniform spacing of ridges and hollows in humid rugged mountains

Despite the influences of infiltration capacity on D, the average value of D_t generally falls within a narrow range for different types of geology as well as for different R: between 8 and 13 km/km^2 (Figure 9). Table I shows that the standard deviation of D_t for each category is comparable to that for D_d and D_s, although mean D_t exceeds that of D_d or D_s. Accordingly, the variation in D_t in terms of the coefficient of variation (standard deviation/mean) is smaller than that in D_d or D_s. Because D_t is a function of the frequency of ridges and hollows on hillslopes, these findings demonstrate that the spacing of the ridges and hollows in the study area tends to be uniform.

Such uniform surface texture is an important physiographic characteristic of the study area, i.e. maturely dissected mountains in a humid region. Hack (1960, p. 95) postulated that the general topography of a typical ridge and ravine topography in humid regions is probably maintained despite the change in relief, although both the erosion rate and the angle and roundness of hillslopes should vary with relief. Thus, he reasoned that the general outline of the present drainage in the Appalachian Highlands may be inherited from prior conditions (Hack, 1960, p. 96). The result of this study is concordant with Hack's (1960) hypothesis for humid mountains. As noted, high-relief parts of the study area are thought to have undergone more extensive Quaternary erosion than low-relief terrains, although both high- and low-relief areas have a similar density of total drainage lines. This observation suggests that erosion in the study area has continued without effecting a change in the spatial distribution of ridges and hollows, because valleys have undergone straight downcutting in the same manner as the development of the antecedent drainage. The present study indicates that lithologic control on the distribution of ridges and hollows is also limited in steep Japanese mountains, although relief and lithology have played a significant role in determining the small-scale valley forms along drainage lines.

In the early stage of dissection of a featureless terrain, D should increase with time and R. In Japan, this relation has been confirmed for several levels of dissected coastal terraces (Tokunaga *et al*., 1980; Kashiwaya, 1983, 1987). For most of the area studied here, by contrast, R exceeds 100 m, reflecting the steep, mountainous character of the area. Thus, the D–R relations described here apply only to steep terrains in Japan. Generalized D–R relations that are valid not only in steep terrains but also in very gentle topography should be sought in future work.

CONCLUSIONS

This paper re-examined relations between drainage density (D) and relative relief (R) for steep Japanese mountains. The drainage networks were constructed using two different criteria, which enabled deeply notched valleys to be separated from shallow hollows. When either type of drainage was analysed, the calculated D varied according to R and bedrock geology. The resulting D–R relations for the study area differ from those for some regions in the United States in that density of deep and narrow channels decreases with R. This difference stemmed from different hillslope processes: widespread slope failure in Japan, gullying of unconsolidated

sediments in the United States. When all drainage lines were included, *D* tended to be unchanged despite differences in *R* and geology, reflecting a uniform frequency of ridges and hollows in humid rugged mountains. I conclude that in Japan *R* and bedrock geology exert major controls on the small-scale valley forms, but only a minor influence on the total density of drainage lines.

The lack of deep gullies on steep hillslopes was reported from Northern Papua, where slope wash combined with mass movement is responsible for smooth, straight profiles of steep slopes (Ruxton, 1967). This observation suggests that *D*–*R* relations there are similar to those for Japanese mountains. The inferred similarity of *D*–*R* relations for Japan and other steep humid regions should be tested in future study.

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